Post-launch Validation of Multispectral Thermal Imager (MTI) Data and Algorithms

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ABSTRACT

Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL) and the Savannah River Technology Center (SRTC) have developed a diverse group of algorithms for processing and analyzing the data that will be collected by the Multispectral Thermal Imager (MTI) after launch late in 1999. Each of these algorithms must be verified by comparison to independent surface and atmospheric measurements. SRTC has selected 13 sites in the continental U.S. for ground truth data collections. These sites include a high altitude cold water target (Crater Lake), cooling lakes and towers in the warm, humid southeastern US, Department of Energy (DOE) climate research sites, the NASA Stennis satellite Validation and Verification (V&V) target array, waste sites at the Savannah River Site, mining sites in the Four Corners area and dry lake beds in Nevada. SRTC has established mutually beneficial relationships with the organizations that manage these sites to make use of their operating and research data and to install additional instrumentation needed for MTI algorithm V&V.

Keywords: Validation, Verification, Ground Truth, Multispectral Imaging

1. INTRODUCTION

The DOE Multispectral Thermal Imager (MTI) satellite will produce large amounts of fairly high resolution imagery over 15 wavebands covering the visible, near-infrared (NIR), short-wave infrared (SWIR), mid-wave infrared (MWIR) and long-wave infrared (LWIR). The imagery will be used to demonstrate enhanced capabilities in a variety of applications, including temperature retrieval, analysis of thermal and particulate pollutant transport in surface water systems and the atmosphere, waste and mining site monitoring, vegetation health and material identification. Verification of MTI's performance in these different applications requires independent radiometric measurements and the collection of necessary collateral data, such as atmospheric temperature and humidity profiles, direct water temperature measurements and target material samples for laboratory spectral analyses.

SRTC was selected as the lead DOE laboratory for ground truth data collections because it has been researching environmental effects of large industrial facilities for more than 30 years at the Savannah River Site (SRS). The SRS is an 800 km^2 former nuclear weapons materials production site in South Carolina. As a result of Cold War plutonium and tritium production at SRS, a number of locations within site boundaries were contaminated with chemical and/or radioactive wastes. SRS is now an Environmental Restoration (ER) site, and an extensive program to contain, stabilize and remove contaminants from those locations has been ongoing since the 1980's. Remote sensing systems have been a key component of the environmental restoration work at SRS for many years. Applications of remote sensing technologies have included thermal imaging of heated water from SRS production reactors as it spread and cooled in SRS streams and the adjacent Savannah River floodplain (Negri and Shines[1]). Another application has been monitoring of vegetation stress caused by thermal and chemical pollutants (Blohm et al.[2]) and gamma radiation surveys of reprocessing and reactor areas. The remote sensing data collections by SRTC (and the nearby Savannah River Ecology Laboratory) have always been accompanied by ground truth measurements for calibration and interpretation of the remote sensing data. Over the years, a comprehensive Geographical Information System (GIS) data base has been built for SRS, including the following categories of information: remote sensing, ground water, surface water chemical and biological, chemical and radioactive monitoring, zoological, botanical and atmospheric (Bresnahan et al.[3]). SRTC will use this experience and information to plan and carry out the MTI ground truth collections.

2. MTI SCIENCE ALGORITHMS

Smith et al.[4] described 16 science algorithms for which ground truth data must be collected. In many cases, one target will provide data that can be used to validate more than one of these algorithms. In order to minimize the number of sites required to fully validate the 16 algorithms, SRTC determined what data is required for validation of all 16 algorithms and derived a set of site characteristics that would be adequate to produce those data. Using the set of site characteristics as a guide, SRTC then developed a list of potential sites, performed an initial screening and then did a more detailed investigation of the remaining sites, including contacts with site management and visits. The 16 science algorithms and corresponding ground truth sites are listed below, followed by brief descriptions of the algorithms and the ground truth sites.

Algorithm	Ground Truth Collection Targets
1. Calibration Correction	Nevada playas
2. Interband Registration	Bridge over Lake Pontchartrain
3. Image reconstruction and Restoration	Bridges, airstrips
4. Physics-based Water and Land Temperature Retrieval	Heated/unheated lakes, NASA target array
5. Robust Water Temperature Retrieval	Heated/unheated lakes
6. Detection of Boundaries of Bodies of Water	Natural and manmade lakes
7. Subpixel Temperature Retrieval	Thermal discharge to cooling lake
8. Industrial Heat Dissipation in Surface Water Systems	Cooling lakes, rivers, bays
9. Industrial Heat Dissipation in the Atmosphere	Cooling towers
10. Cloud Masks	Oklahoma ARM site, large lakes
11. Thin Cirrus Detection/Removal	Oklahoma ARM site
12. Scattering and Absorption by Aerosols	Oklahoma ARM site
13. Columnar Water Vapor Retrieval	Oklahoma ARM site
14. Vegetation Health	Savannah River Site
15. Water Quality and Bathymetry	Crater Lake, southeast U. S. lakes
16. Material Identification	Savannah River Site, uranium mines

1. Calibration Correction

MTI has been extensively calibrated at Los Alamos using well-known source radiances traceable to standards at the National Institute of Standards and Technology (NIST). After launch, maintenance of the laboratory calibration will rely on on-board calibration sources consisting of two blackbodies, two lamps, and a reflector on a calibration wheel near the focal plane. Full-aperture calibrations will use the aperture door assembly, which is both a temperature-controlled blackbody and a diffuser for solar calibrations (Clodius et al.[5]). Also after launch, we will perform vicarious calibrations using some combination of measurements of ground surface and atmospheric properties by ground-based devices and measurements from an aircraft. We will use the methods described by Slater et al.[6] which require that the surface being imaged be as large and uniform as possible. We will use the sun, moon and selected stars for additional vicarious calibrations.

SRTC plans to take ground-based measurements at one of the desert playas in Nevada or California. Both of these sites have been used extensively to check satellite calibrations because they are very flat and show little spatial variation in spectral properties over distances that are large relative to MTI's resolution (5 m in visible wavebands, 20 m in infrared). SRTC will measure radiances in the reflective wavebands (0.4 to 2.5µ) with an ASD field spectrometer. An automated balloon-borne instrument package will take concurrent atmospheric profiles of humidity and temperature. SRTC will use a Sun photometer to measure aerosol content along MTI's imaging path. SRTC will also probably use visibility and particle measurement sensors.

2. Interband Registration

Pixels from each of MTI's 15 wavebands must be registered to the same frame of reference so that an object's location in a scene is the same in all of the images. Interband registration is crucial to most MTI applications, including material identification, water temperature, columnar water vapor and vegetation health. Scenes with long straight objects that are accurately geo-located are best suited to testing of interband registration algorithms. Examples include bridges, channels and landing strips.

SRTC has selected three objects as candidate line sources for interband registration testing: 1) bridges and railroads (Figure 1) over Lake Pontchartrain just north of New Orleans, 2) the Davis County Causeway that extends out into the Great Salt Lake, and 3) the airstrip at Dahlgren Naval Base in Virginia. SRTC plans to accurately geolocate one or more of these candidate line sources and characterize their spectral properties.

Figure 1: Railroad extending over Lake Pontchartrain, Louisiana

3. Image Restoration and Reconstruction

Image restoration algorithms attempt to correct the measured image for degradation caused by sources of blurring and noise. Blurring can be caused by atmospheric turbulence, scattering of light from adjacent surface elements and aerosols, telescope point spread function, motion and jitter during image acquisition and satellite electronics. Sources of noise include thermal noise, correlated noise (streaking) and quantization noise.

The same objects that will used for testing of interband registration algorithms will also be suitable for testing of image restoration and reconstruction algorithms. In addition, uniform surfaces such as lakes with weak temperature gradients on calm days can be used to quantify the amount of correlated noise.

4. Physics-based Water and Land Temperature Retrieval

MTI's physics-based temperature retrieval algorithm uses MODTRAN to iterate columnar water vapor and atmospheric temperatures over a small range until the retrieved surface temperature is the same for all spectral channels and at the same time the measured radiances are matched. For land surfaces during the day, the NIR and SWIR channels would be used to identify the surface material, emissivities would be taken from standard sources and the iteration would be performed based on those emissivities.

SRTC will provide highly accurate water temperatures from unheated lakes at the Savannah River Site and the Oklahoma ARM site and a cooling lake at a nearby power plant to test the temperature retrieval algorithm. The data provided by SRTC will include a correction for the difference between the true surface temperature actually measured by the satellite and the bulk water temperature, which is usually the quantity actually measured. Remote sensing systems measure the temperature of a very thin layer or “skin” of water which is less than one millimeter thick and which usually is colder than the bulk water temperature just below. The skin temperature is lower because it strikes a balance between evaporative energy losses to the atmosphere above and the upward transport of heat from the bulk water layer below. SRTC will also provide atmospheric profile data from those three locations.

For land temperatures, SRTC will use surfaces such as those at the NASA Stennis V&V Target Array, which are large and uniform and characterized spectrally.

5. Robust Water Temperature Retrieval

The MTI robust water temperature retrieval algorithm uses a statistical approach to determine water temperature. This approach models radiation transport for the five MTI thermal wavebands through a variety of atmospheres. For each channel and both look angles the Top-Of-Atmosphere (TOA) brightness temperature is computed as a function of surface water temperature. Linear regression is used to relate water surface temperature to TOA brightness temperature.

SRTC will use the same sites and methods used to validate the physics-based temperature retrieval algorithm to validate the robust water temperature retrieval algorithm. Our goal is to collect at least 30 usable images of the ground truth sites for robust and physics-based temperature retrieval to ensure that the results for temperature retrieval are statistically significant.

6. Detection of Boundaries of Bodies of Water

This algorithm will compute expected reflectivity from a water surface and compare those values to observed reflectivity in a scene. It will make use of MTI bands A through D (visible and near infrared) and the low reflectivity of water to discriminate between land and water pixels. The algorithm will account for the somewhat higher reflectivity of turbid water and the effect of chlorophyll on band B (green). The expected reflectivity modeled by the algorithm will include the effects of wind speed, angle of incidence and angle of detection.

Many of the ground truth sites have bodies of water, including irregular ocean shorelines, Crater Lake (which contains Wizards Island), power plant cooling lakes, SRS lakes and a small pond at the Oklahoma ARM site. These water bodies will constitute a diverse set of targets with different boundary configurations, temperatures and elevations for testing of the detection algorithm for water body boundaries.

7. Subpixel Temperature Retrieval

The subpixel temperature retrieval algorithm is directed primarily at recovering water temperatures from narrow channels or small bodies of water, which have many mixed land-water pixels. The algorithm assumes that some pure (unmixed) pixels are available in the scene, which can be used to compute columnar water vapor and effective atmospheric temperature with the physics-based temperature retrieval algorithm. Radiance in the five MTI thermal wavebands, an emissivity estimate for the land surface, and an estimate of the fractional coverage of the pixel by land and water (derived from visible wavebands) are also needed. With these inputs, temperatures for the water and land parts of the pixel can be derived by finding a best fit to the measured radiances from the five MTI thermal wavebands.

Surface thermal discharges into power plant cooling lakes produce areas of water that are much warmer than adjacent land. These discharge locations are well suited to testing of this algorithm.

8. Thermal Energy Discharge Rates Into Surface Water Systems

This algorithm uses MTI imagery to determine the rate at which waste heat is discharged by an industrial facility to water bodies such as a cooling lakes, rivers and bays. Power plants and many other industrial facilities frequently use surface water systems to dissipate large quantities of waste heat. The temperature and amount of the water being discharged determine whether it has any adverse environmental effects. The thermal plumes created by the discharge of waste heat to the environment are well suited to analysis by thermal imaging. This algorithm combines calibrated thermal imagery from MTI, 3-D hydrodynamic modeling, local meteorological data and the physical characteristics of the surface water system to find the discharge rate (Garrett and Hayes[7]). Given the discharge rate, the amount of heat being injected into the environment can be found, and information about transport of other non-visible pollutants is generated. Figure 2 compares observed surface temperatures from Daedalus imagery of a SRS cooling lake to simulated temperatures for the same time generated by this algorithm.

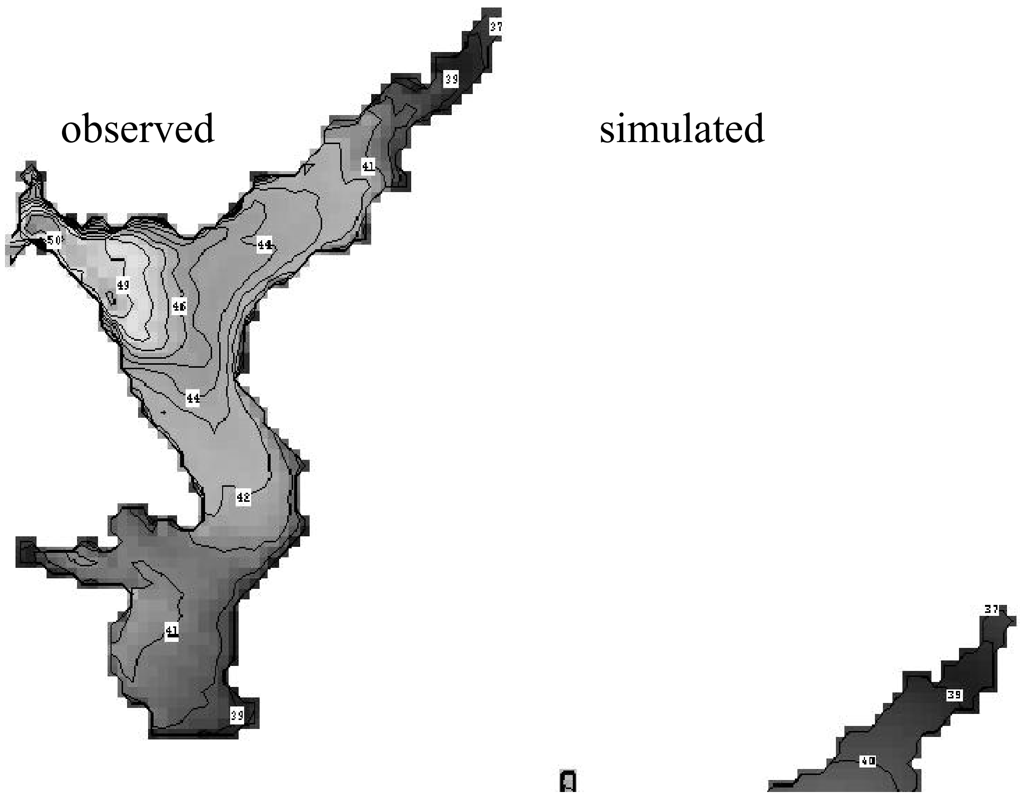

Figure 2: Observed and simulated Savannah River Site cooling lakes.

SRTC will validate this algorithm with data from four power plants in different parts of the country that use cooling lakes, cooling canals and ocean discharge to dissipate waste heat.

9. Thermal Energy Discharge Rates Into the Atmosphere

This algorithm uses MTI imagery to determine the rate at which waste heat is discharged to the atmosphere by an industrial facility. Power plants and other industrial facilities often use natural draft or forced draft cooling towers to dissipate waste heat in the atmosphere. Cooling towers can have several local impacts on the environment, including fog generation, icing, light snowfall and mist formation and cumulus cloud initiation. This algorithm will use calibrated thermal and visible MTI imagery, 3-D hydrodynamic modeling, local meteorological data and cooling tower specifications to estimate the rate at which water mass and enthalpy are being discharged to the atmosphere (O'Steen[8]).

SRTC will collect ground truth data at the Vogtle power plant in Georgia to validate this algorithm. The Vogtle plant uses natural draft cooling towers. Ground truth data will include simultaneous visible and thermal images of the cooling tower plumes, ambient meteorology and internal cooling tower temperatures and flow rates. The visible imagery will be used to compute the volume of the cooling tower plumes at the time images are taken by MTI. The thermal imagery will be compared MTI imagery and with radiative transfer calculations based on plume simulations. Figure 3 shows a series of photographs and simulated Vogtle plumes under calm meteorological conditions.

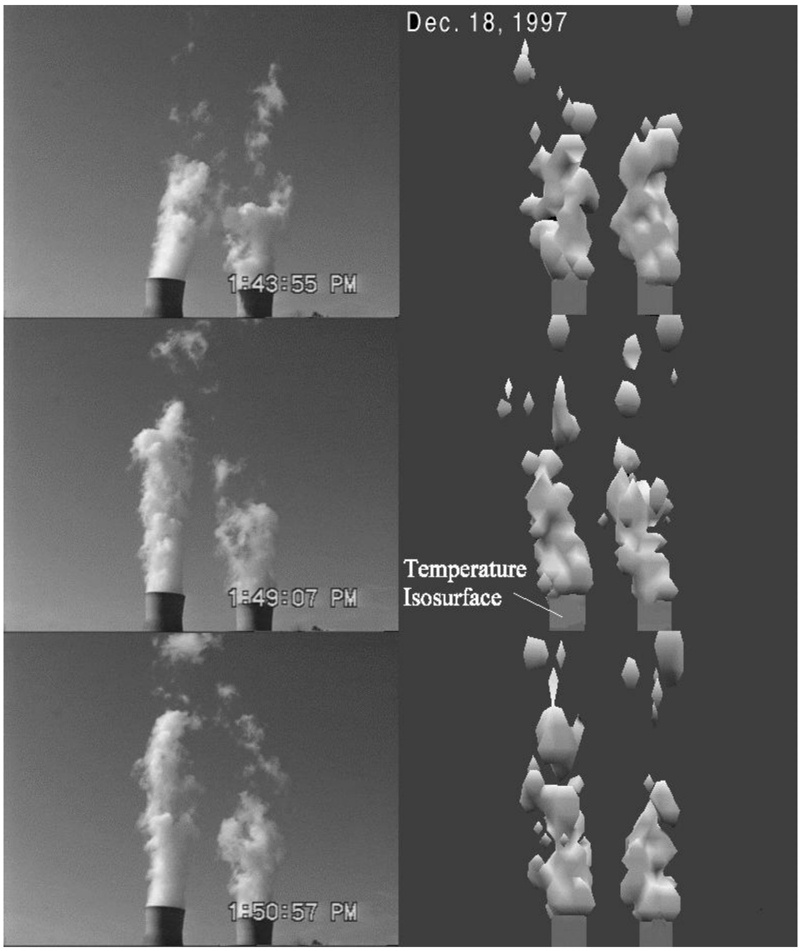

Figure 3: Camcorder images and simulated cloud water plumes for Vogtle plumes. The cloud water isosurface is at 0.01 gm/kg. The tower is visualized with a temperature isosurface at the tower exit air temperature.

10. Cloud Masks

This algorithm will attempt to identify and flag clouds in MTI images by combining threshold BRDF values across the visible and near infrared part of the spectrum with low brightness temperatures in the thermal part of the spectrum. It will attempt to discriminate between low clouds and surface objects through use of the nadir and 60° images that MTI will take on a single pass over a target. The algorithm will also determine the areas shadowed by clouds because those areas will have only the diffuse component of reflected radiation.

Ground truth sites with large uniform surfaces such as water will provide the simplest tests of this algorithm. An excellent target is Lake Pontchartrain because it has uniformly turbid water and often has small cumulus clouds over it. Any of the other sites could be used as more challenging test locations, with the Crater Lake area offering the opportunity to discriminate between low clouds and snow. The Oklahoma ARM site will be attractive because its atmospheric characterization includes whole-sky cloud measurements.

11. Thin Cirrus Detection/Removal

This algorithm uses MTI band H (1.36-139µ) to detect the presence of thin (sub-visible) cirrus clouds, which reflect solar radiation in this waveband that would otherwise be absorbed by water vapor in the lower depths of the atmosphere. It also uses band H to correct for the effect of thin cirrus clouds on the visible and near infrared channels (A through F). Since this algorithm can only be used during the day, some effort will be made to develop an algorithm that detects and removes the effects of thin cirrus at night. This appears to be possible, given MTI's well-calibrated thermal radiometry.

The ARM site in northern Oklahoma will provide the comprehensive atmospheric measurements needed to validate this algorithm. The central facility has a micro-pulse lidar, which is sensitive enough to detect sub-visual cirrus.

12. Scattering and Absorption by Aerosols

This algorithm corrects the MTI visible and near-infrared channels for aerosol path radiance to derive true ground reflectance. The algorithm will use dark targets in the scene, such as thick stands of trees, to determine surface reflectance in the SWIR channel O where atmospheric scattering and absorption are very weak. Reflectance values in MTI channels A and C are highly correlated with channel O reflectance for dark targets. Aerosol optical depths in channels A and C can be calculated from the measured TOA radiances and the calculated surface reflectances. Remaining channel aerosol optical depths can be determined empirically through use of curve fits through channel A and C data. Given the aerosol optical depths for all channels, surface reflectances for the non-dark target scene pixels can then be calculated.

Crops such as sorghum and soybeans are grown on the farms surrounding the Oklahoma ARM site. The reflectances of these crops during growing season when they are dark green will be collected. These spectra, plus the comprehensive atmospheric characterization at the ARM sites (including aerosol measurements) will provide a ground truth data base for validation of the algorithm.

13. Columnar Water Vapor Retrieval

This algorithm will derive the atmospheric columnar water vapor content using reflected sunlight and the 0.94 micron water vapor absorption band (MTI Band F). A new technique called Atmospheric Pre-corrected Differential Absorption (APDA) has been developed which based on preliminary tests appears to be more accurate than traditional Continuum Interpolated Band Ratio (CIBR) methods over many surface types. APDA improves on the empirical CIBR method by adding physics based on radiative transfer.

Validation of the algorithm will require atmospheric profiles of humidity and temperature as a function of pressure, simultaneous ground-based sun photometer measurements of optical depth, uniform ground coverage with a 10 nm sampling reflectance spectrum, and cross-calibration of MTI channels E, F and G with an airborne imaging spectrometer such as AVIRIS. We hope to have some simultaneous AVIRIS collections over the desert playas and the NASA-Stennis V&V target array in Mississippi. The Oklahoma ARM site is another verification site, since it will have the atmospheric, sun photometer and other radiometric data.

14. Vegetation Health

The goal of this algorithm is to identify vegetation that has been stressed by atmospheric, surface or subsurface releases of pollutants from industrial sites. Since there are many natural sources of stress for vegetation, e.g., lack of water, discrimination between anthropogenic and natural sources of stress will require time series of images and/or collateral information about the industrial site. The algorithm makes use of the fundamental observation that the chlorophyll content of vegetation under stress decreases, and along with it the relative peak in reflectance of green light (MTI Channel B). The algorithm will also use Channel I (1.55 to 1.75µ) to attempt to discriminate between stress caused by lack of water and other types of stress (Hunt et al.[9]). The algorithm will use a neural network to classify leaf reflectance data that has been binned and averaged over six MTI channels.

Vegetation stress has been studied at the Savannah River Site (SRS) for many years as a part of the environmental restoration program for areas affected by chemical and radioactive contaminants as a result of Cold War nuclear materials production (Blohm et al.[2]). Forested areas near SRS's D-Area have been affected by acidic runoff from coal ash and have already been the subject of research.

15. Water Quality and Bathymetry

Since there is an extensive literature on retrieval of water quality parameters from remote sensing data, we will apply existing methods and MTI channels A,B and C (blue, green, red) to retrieve water quality data. Primary quantities of interest are chlorophyll content, suspended sediments and yellow substance (dissolved organic matter). Codes such as 6S will be used in the retrieval algorithm because they include relationships between water color and chlorophyll and the effects of wind on water reflectance.

The turbid lakes of the southeast U. S. typically have high chlorophyll contents due to high algal concentrations and even algal mats. Sites include power plant cooling lakes and unheated lakes at SRS, which are monitored as part of site environmental programs. Water quality is also a research focus at Crater Lake which is an extremely clean body of water and which will provide data that sharply contrasts with imagery from the southeast U. S. lakes.

16. Material Identification

A k-means clustering algorithm will be used to distinguish between various types of materials within an MTI scene. This algorithm will use the three visible MTI channels (A, B, C), the near IR channel D and the short-wave IR channels I and O. The cluster centers will be determined from a library of spectral reflectance data for a wide variety of man-made and natural materials. The algorithm will assign each MTI pixel to one of the material categories.

The Savannah River Site (SRS) combines several large industrial facilities with large areas of natural forested terrain. There are asphalt, concrete and gravel roads, large metal waste tanks, coal piles, buildings with rooftops made of various materials and painted surfaces. Natural surfaces include forest, swamp, bare soil and waste sites that have clay caps with grass on top. Another target will be the uranium mining sites and associated tailings in New Mexico and Arizona.

3. Ground Truth Measurements

3.1 Radiometric Measurements

The intervening atmosphere between satellite and ground level surfaces affects the quality of the imagery recorded by the satellite. The MTI satellite characterizes ground targets by measuring reflected and emitted radiance from 15 spectral bands in the range of 0.45 to 10.70 microns. The broad spectral range observed by the satellite encompasses the visible, NIR, SWIR, NWIR and LWIR. Present technology cannot satisfy all ground truth requirements needed by the satellite with a simple instrument. The broad spectral region has been subdivided in smaller regions based on availability of instrumentation, technical application, spatial and wavelength resolution.

MTI spectral bands A-D and O are spectral bands primarily used for material identification. Bands E-F are used for the determination of atmospheric water vapor and band H for detection cirrus clouds. Band I will provide information related to vegetation stress through measurement of leaf water content. The retrieval of the temperature's surface is accomplished with the remaining 5 bands (J-N).

The FR spectroradiometer (Figure 4) and the Sun Photometer manufactured by Analytical Spectral Devices (ASD) and the University of Arizona respectively, will be used to measure the visible and near infrared spectral regions. The primary function of the ASD FR spectroradiometer is to provide relative reflectance and absolute radiances of ground targets. The ASD FR spectroradiometer will be used in the 0.35 to 2.5-micron spectral range encompassing bands A-I and band O. The Sun Photometer's primary purpose is to evaluate the skies' optical depth and therefore the aerosol concentration by measuring the solar radiation reaching the earth's surface. The Sun Photometer uses 10 spectral bands from 0.38 to 1.03 microns to calculate the sun's radiance.

Figure 4: ASD FR spectroradiometer.

The water and ground surface temperature is calculated from the radiance of the 5 J-N bands in the MWIR and LWIR. Temperature measurements will be acquired with accurate glass thermometers traceable to NIST, hand-held digital thermometers, point radiometers, and imaging radiometers. Surface temperature measurements will be recorded using Heimann point radiometers manufactured by Heitronics. The radiometer's accuracy will be verified using blackbodies manufactured by MIKRON Corp. The temperature of extended surface areas will be measured using imaging radiometers manufactured by Inframetrics Corp. Two cameras from Inframetrics will be used to characterize the surface (model 760 and a portable SC2000). A Fourier transform infrared spectrometer manufactured by Midac Corp. will be used to measure the spectral radiance of the 5 bands used by the MTI satellite.

3.2 Skin Temperature Measurements

In the past decade, the increased accuracy of satellite measurements has focussed attention on the difference between the temperature of bulk seawater (uppermost 10 centimeters of water) and the temperature of the 'skin' (the upper 1mm). This is because the skin temperature, which is measured by satellite, is typically 0.5 – 1.0°C less than the bulk temperature, the quantity usually measured from ship or buoy.   The skin effect is more significant over bodies of fresh water because of the greater variability of water temperature, air temperature, wind and humidity. The skin temperature depression can be as large as 3°C over heated bodies of water, or even positive, as is the case of warm air over cold water.   Understanding the skin temperature effect is of practical importance for ground truth programs because the bulk temperature is much easier to measure accurately than the skin temperature.

Although the skin temperature effect has been studied in the past (Schluessel et al.[10]), a reliable method to estimate its size and variability for a range of conditions is not available. The most important factors which govern the skin temperature effect are the exchange of IR radiation between the water surface and the atmosphere, heat transfer from the surface to the atmosphere via latent and sensible heat flux, and mixing of the sea surface. Typically, the skin temperature depression is increased by radiative loss and evaporation and decreased by turbulent transport of heat upward through the bulk water layer.

To study the skin temperature effect, an experimental apparatus has been constructed, which can be anchored in bodies of water, and which measures the air temperature, humidity and wind speed, the broadband IR and visible heat exchange, the water temperature and the skin temperature. The skin temperature is measured with an 8-14 micron radiometer, which is positioned approximately 0.5 meters above the water. The apparatus is shown in Figure 5.

Figure 5: Fabrication of skin temperature experimental apparatus.

The skin depression is determined by comparing the temperature measured with the radiometer (skin temperature) and a thermocouple at 10 cm below the surface (bulk temperature). Because of the inherent difficulties of this approach, the skin temperature depression was also determined by comparing radiometer measurements of the natural water surface and the ‘stirred’ surface. The ‘stirred’ surface temperature was obtained by pumping a jet of water from 10cm below the surface into the radiometer’s field of view. Because the skin depression takes ~10 sec to form, the stirred temperature will be equivalent to the bulk temperature.

Figure 6 shows results obtained from an unheated SRS lake on March 18 and 19 of 1999. The figure shows the bulk water temperature at 10 cm deep (thermocouple), the radiometer temperature of the natural water surface, and the radiometer temperature of the pumped water (the vertical bars at 10 minute intervals). The pump was operated every 10 minutes for 10 seconds. The radiometer “pump temperature” is the average of the radiometer measurements at 4, 6, 8 and 10 seconds after the pump was turned on. Ideally, the bulk water temperature will equal the temperature of the pumped water as measured by the radiometer. Figure 3 shows, however, that the radiometer pumped water temperature is ~0.2C cooler than the bulk temperature. This is due to a bias of the radiometer of -0.05C compared to the thermocouple and to the contribution to the radiometer temperature from reflected (cooler) sky radiation. This effect is estimated to about –0.2C.

An interesting feature in Figure 6 is the greater variability of the temperature of the natural water surface compared with the pumped water temperature; both obtained with the radiometer. This difference is surprising since the former is an average of 30 values while the latter is an average of 4 values. However, this difference is believed to reflect the large variability of the skin temperature in very light winds (less than 1 m/s), when large skin temperature depressions can form because in the absence of mixing in the bulk water layer. The results also suggest that the skin temperature effect may be most difficult to account for over small inland bodies of water on clear nights, when the winds will be near calm. Conversely, the most reliable estimates of the skin temperature may be possible during windy days, when the water surface and atmospheric boundary layer are well mixed.

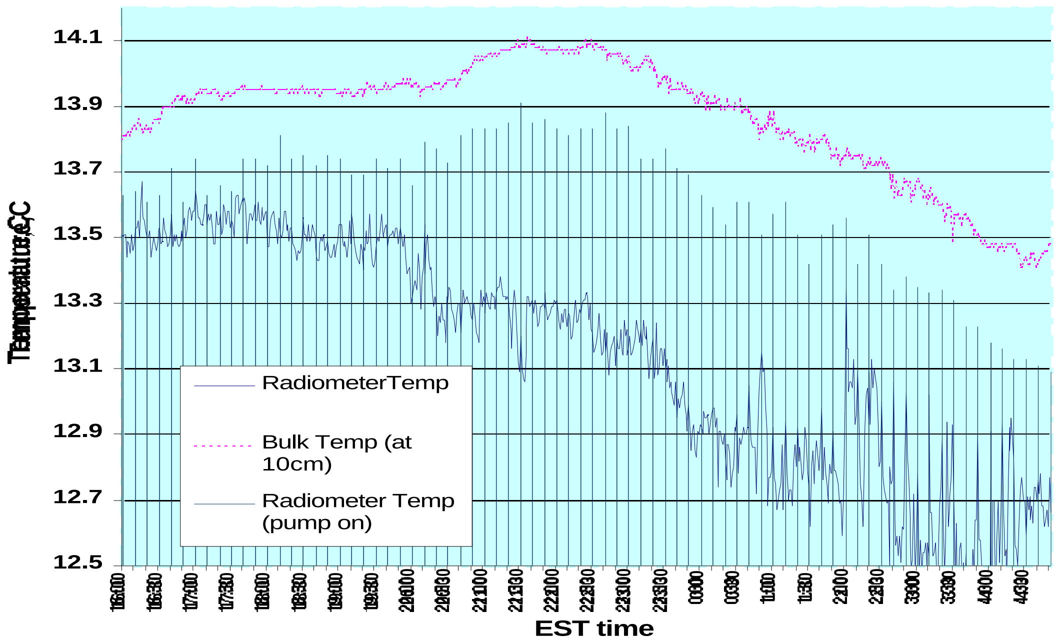

Figure 6: Comparison of measured skin and bulk water temperatures in SRS cooling lake.

3.3 Atmospheric Characterization in Support of MTI Ground Truth Collection

MTI temperature retrieval algorithms have been developed to eliminate interference from atmospheric constituents such as water vapor, aerosols, ozone and air pollution. Of the four constituents listed, only column-integrated water vapor will be derived from the image data and output as a water vapor image. The success of the MTI algorithms for accounting for atmospheric effects will be evaluated indirectly through comparisons of image derived water temperature and ground truth measurements. It is desirable to quantify the accuracy of the temperature retrieval as a function of meteorological conditions and to collect sufficient ground truth data to determine causes for temperature retrieval errors leading to subsequent algorithm improvement. This will be accomplished at two ARM sites operated by DOE: the Great Plains ARM Site in north-central Oklahoma, near Ponca City and the Tropical Western Pacific ARM Site about 1500 km east of New Guinea on the island of Nauru. These sites utilize state-of-the-art equipment to characterize the complete atmosphere using radiosondes, microwave radiometers, LIDARs, numerous radiometers, radar and all-sky cameras.

At least two models used by MTI require estimates of boundary-layer meteorology such as wind speed, humidity, and air temperature, in addition to information derived from the image. One model is used to estimate waste heat from cooling tower plumes. The other model is used to calculate bulk water temperature from the image-derived skin temperature. A meteorological model such as RAMS or ETA will provide estimates of the boundary layer meteorology or, if available, interpolation from near-by weather observations. As above, model accuracy can be determined directly from ground truth data for a few sites and inferred for others. The cooling tower model will be evaluated at Plant Vogtle, GA and the skin temperature model will be evaluated at SRS and nearby cooling lakes. Model accuracy will be dependent upon model assumptions and boundary-layer meteorological data but will be affected by the accuracy of the temperature retrieval described above. In order to assist in the evaluation process, atmospheric water vapor and temperature profiles will be measured with the balloon-borne Atmospheric Meteorological Research System (AMRS) and atmospheric aerosols will be measured with a 6-channel spectral photometer. These measurements are not as complete as those made to characterize the atmosphere at the ARM sites but will provide a means by which model errors can be separated from those affecting temperature retrieval.

Measurements of surface water temperatures are critical for ground-truth corroboration against MTI satellite imagery. Typical monitoring locations include areas where large temperature gradients are present such as power plant cooling lakes. Measurements must be made within the upper 10 cm of the water body to ensure a proper representation of the surface water temperature. Where necessary, buoys or other similar floatation devices will be used to maintain the proper monitoring level. Probe types include precision thermocouple or platinum resistance devices that are calibrated against traceable standards. Data will be collected locally and, in some cases, are made available remotely via telecommunication hardware in near-real time.

4. SUMMARY

We have used the 16 MTI science algorithms as our guide for selection of ground truth collection sites. These sites are in a variety of climatic regimes including humid subtropical (Southeast U. S.), hot dry desert (Southwest), cool, high altitude (Pacific Northwest) and cool maritime (Northeast). Collectively, these sites will provide data needed to validate all of the MTI algorithms. The data will be collected in collaborative relationships with other government agencies, universities and private organizations.

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